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Annual Report

to the

Air Force Office of Scientific Research

of

a Program of Research

in

Subpicosecond Electrooptic Sampling

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Improvements made to the electro-optic sampling system have been instrumental to the demonstration of world record performance of an integrated photodiode/electrical sampler. Measured, undeconvolved time response of the circuit was 1.8ps, corresponding to an electrical 3dB bandwidth of 200GHz. To measure such a short time response, the pulse width of the electro-optic sampling system was reduced, and a frequency doubling stage was added. The electro-optic sampling system was also used to make the first measurements of broadband electro-optic response of organic polymers. The use of these polymers, as well as erbium doped fiber optical amplifiers, to increase the utility of electro-optic sampling techniques has been investigated.

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Summary:

The electro-optic sampling system initially developed under AFOSR contract #F49620-85-0016 was instrumental in the testing of an optoelectronic integrated circuit consisting of a photodiode and an electrical sampler. World record performance of 1.8ps total response time, corresponding to a bandwidth of 200GHz was achieved. In order to make these measurements, the time response of the electro-optic sampling system was improved by the addition of a second stage of optical pulse compression. An optical frequency doubling stage was added to produce pulses to excite the photodiode under test.

A preliminary investigation has been made of changes to the electro-optic testing system which could yield a more practical, commercially feasible system. These changes revolve around the use of erbium doped fiber optical amplifiers and fast photodiode / electrical receivers. This will allow the use of commercially available instruments like spectrum, network, and transition analyzers to make electro-optic measurements.

The electro-optic sampling system supported by this contract has also been instrumental in the characterization of organic electro-optic materials funded under U.S. Army Research Office contract DAAL03-88-K-0120. These electro-optic materials can be used to extend the electro-optic testing technique to circuits which are either built on nonelectro-optic substrates or packaged into multichip modules. The electro-optic sampling system was used to measure the electro-optic coefficient of a polymeric organic electro-optic material, and allowed us to demonstrate for the first time that these materials can exhibit a broadband electro-optic response to 40 GHz.

Report:

Improvements to the existing EO sampling system

In order to test the high speed photodiode / electrical samplers described in the next section, several improvements had to be made to the electro-optic sampling system. The time resolution of an EO sampling system is limited by both the laser pulsewidth and the pulse-to-pulse timing jitter. The existing system typically produced optical pulses of 1.2 ps FWHM duration with 300 fs of pulse-to-pulse timing jitter. By adding the option of a second stage of optical pulse compression, we have been able to attain subpicosecond pulses. A simple kinematically-mounted mirror allows the user to choose between single, or double stage optical pulse compression. With the double stage system, the optical pulse duration is typically 300 fs. Because we are interested in testing GaAs photodiodes, we added a second-harmonic generation capability. With a 1.0 mm thick KTP crystal, we were able to achieve 400 fs of 0.532 μm wavelength light. By decreasing the thickness of our doubling crystal to 0.5 mm, we should be able to achieve 200 fs pulses at 0.532 μm.

In addition to a second stage compressor, a photodiode testing probe station was built. The 0.532 μm light is fiber-optically delivered to a modified microscope which both focusses the 0.532 μm light to 5 μm spot size and images the circuit to a CCD camera for ease of alignment. As with our other probe station, this new one allows for backside electo-optic probing, and is equipped with coplanar waveguide probes to provide bias to the circuit.

High-Speed Monolithic Photodiode/Sampler

Photodetectors play a fundamental role in optical communication and measurement systems. In communications systems, faster detectors could enhance system bandwidths; in measurement systems, they could measure picosecond optical waveforms from mode-

locked lasers, and optical and optoelectronic devices. Because presently available oscilloscopes only have 3-dB bandwidths up to 50 GHz, the large bandwidth technique of electro-optic sampling has to be used to measure the response of these photodetectors. The device speed is then indirectly determined by a deconvolution of the system response from the measured data. To overcome this measurement problem, we have monolithically integrated a high-speed Schottky photodetector with an all-electronic sampler. Without using deconvolution, we are able to measure a temporal response of 1.8 ps FWHM, corresponding to a 3-dB bandwidth of 200 GHz. The device is pictured in Figure 1.

The circuit schematic of the monolithic photodiode/sampler is shown in Figure 2. The output of the photodiode is connected to the sampler through a coplanar transmission line. The step-like waveform produced by the non linear transmission line (NLTL) strobe is differentiated by the shorted transmission lines, resulting in a voltage pulse across the sampler diodes. This turns on the sampling diodes for the duration of this electrical pulse and enables the sampling capacitors to sample the photodiode signal on the transmission line. The sampled signal is then filtered out by using resistors.

Using the second stage compressor with the KTP doubling crystal, we excited our photodiode/samplers with 0.532 μm light pulses with a duration of 400 fs. The sampled output of the photodiode signal is shown in Figure 3a. We biased the device at 4.5 V, which corresponds to a 0.25 μm depletion region. At this bias voltage, we measured a 750 fs risetime and a 1.8 ps FWHM pulses. The asymmetry of the measured output confirms that we are not laser pulse limited. This output corresponds to a total system response which includes contributions from the photodiode impulse response, the sampler aperture time, the laser pulse duration, the laser timing jitter (<300 fs), and the microwave synthesizer jitter. When these effects are considered in a simple sum-of-squares convolution, we estimate the response of the photodiode to be about 1.6 ps. Given the 0.25 μm depletion width, this estimate yields an average carrier velocity of $1.6 * 10^7$ cm/s, which may be indicative of velocity overshoot.

We show the Fourier transform of Figure 3a in Figure 3b. The dashed line is the Fourier transform of all the data points. The solid line is the Fourier transform of the measured output without the baseline noise. The overall system response has a 3-dB bandwidth of 200 GHz. Our photodetector's measured responsivity was 0.15 A/W which corresponds to an external quantum efficiency of 33% at 532 nm.

Future testing will include electro-optic sampling of these circuits. Using our new probe station and second stage compressed pulses, we hope to study the electron transport properties in these high-speed devices.

Towards a More Practical Electro-optic Testing System

A preliminary investigation into using optical amplifiers to make a more practical electro-optic testing system has begun. The concept was discussed in the proposal for a follow-on to this contract, and is briefly restated here. The idea is a departure from the "fast optics, slow electronics" approach which is characteristic of the use of a pulsed laser source and a slow electrical receiver to detect fast waveforms on an electrical circuit. This approach may be described as "slow optics, fast electronics", which uses a CW laser source which is electro-optically modulated by the circuit under test, and is detected by a fast photodiode and electrical receiver. A realistic fast electrical receiver has a higher noise floor than the slow electrical receiver, so optical amplification of the electro-optically modulated laser beam before the photodiode is key to building a sensitive electro-optic measurement device. A schematic of the system is shown in Figure 4. By changing the setting of the optical waveplate providing the bias point in the electro-optic modulation transfer function, and using an optical amplifier after the polarization analyzer, a larger modulation depth for a given circuit voltage can be achieved. This larger modulation generates a proportionately larger signal in the receiver so that the higher receiver noise is overcome. The benefits of this approach are that 1) a simple, inexpensive, commercially available laser source can

be used; 2) several commercially available receivers such as spectrum analyzers, network analyzers, and microwave transition analyzers can be used, providing useful information to the circuit designer; and 3) detection sensitivity is not sacrificed.

The key to this approach is the use of an optical amplifier. Recent advances in the development of erbium doped fiber optical amplifiers (EDFA) for optical communication systems can be applied directly to this system. These amplifiers provide high (40dB) polarization insensitive gain, and have low noise figures. They can be pumped efficiently by semiconductor laser diodes, so that the entire electro-optic testing system can be highly integrated, and very compact.

Early work has just begun to build an EDFA, and to characterize the gain, noise, and output power.

Organic Electro-Optic Materials for High Speed Integrated Circuit Probes

Another, and complementary, improvement to the electro-optic sampling system can be made by probing an optical element having a larger electro-optic effect than GaAs. The larger electro-optic effect would increase the system's signal to noise ratio with all other factors constant, and allow for greater voltage sensitivity. Rather than sampling the circuit via the GaAs substrate, an external electro-optic element brought into contact or near-contact with the circuit under test, would be optically sampled. For this approach to be practical, the external element would have to be immersed in a significant fraction of the circuit fringe fields while not adversely affecting its operation through loading effects. This application requires, therefore, a material which possesses both a large, broadband electro-optic effect and a low microwave dielectric constant. In addition to potentially improving the system's sensitivity-bandwidth product, probing an external electro-optic element extends electro-optic sampling techniques to circuits built on nonelectro-optic substrates or into multichip modules.

In a related project [funded by DARPA through the U.S. Army Research Office under contract DAAL03-88-K-0120] the use of organic electro-optic materials in electro-optic sampling applications is being investigated. A summary of some of the initial results from the ARO sponsored research follows.

For the initial studies, the organic material used was a Disperse Red 1/poly(cyclohexyl methacrylate) guest/host system. DR1 is a highly polar dye that exhibits a large electro-optic coefficient. The sampling geometry used is shown in Figure 5. A coplanar waveguide transmission line (CPW) was used as the circuit under test. The DR1/PCMA layer was poled normal to the surface between the CPW and a continuous counter electrode (not shown) deposited on top of the organic layer. The poling procedure is needed to partially align the DR1 molecules and create a macroscopic electro-optic coefficient. The counter electrode is removed after poling to allow the optical probe beams to sample the circuit via the organic layer. Only phase modulation of the probe beam is produced, so a reference beam is needed to facilitate the conversion to amplitude modulation.

GaAs was chosen as the substrate material since it could serve as a reference electro-optic material. Taking the ratio of the signals obtained by sampling the DR1/PCMA layer to those obtained by sampling the CPW via the GaAs substrate yields the electro-optic frequency response of the guest/host system. The DR1/PCMA electro-optic frequency response is shown in Figure 6. Within the range and accuracy of the data and under the sampling conditions used, the frequency response of the DR1/PCMA material is flat. This study demonstrates for the first time that polymeric organic electro-optic materials can exhibit a broadband electro-optic response to 40 GHz.

To demonstrate the electro-optic sampling of an actual circuit, a GaAs die containing a nonlinear transmission line (NLTL) was coated with a DR1/PCMA film which was then poled on top of the circuit. The bandwidth of the shock front generated in the NLTL used for the DR1/PCMA sampling tests was 55 GHz. Electro-optic sampling of the circuit via the GaAs substrate showed essentially no change in the circuit characteristics as a result

of the DR1/PCMA coating. The signal obtained from sampling the NLTL from the organic side is shown in Figure 7 and is nearly identical in from to that obtained via the GaAs substrate. The fact that the signal bandwidth was preserved in the DR1/PCMA waveform indicates that the organic frequency response is flat to 55 GHz.

Publications

U. Keller, K.D. Li, B.T. Khuri-Yakub, D.M. Bloom, K. J. Weingarten, and D. C. Gerstenberger, "High Frequency Acousto-optic Mode Locker for Picosecond Pulse Generation," Optics Letters **15**, (1), 45-47 (January, 1990).

R. A. Marsland, M.S. Shakouri, and D.M. Bloom, "Millimeter-Wave Second Harmonic Generation on a Nonlinear Transmission Line," Electronics Letters **26**, (16), 1235 (August 1990).

E. Özbay, K.D. Li, and D.M. Bloom, "2.0 psec GaAs Monolithic Photodiode and All-Electronic Sampler," The Topical Meeting on Picosecond Electronics and Optoelectronics, Optical Society of America, Salt Lake City (March 1991).

E. Özbay, K.D. Li, and D.M. Bloom, "2.0sp, 150 GHz GaAs Monolithic Photodiode and All-Electronic Sampler," IEEE Photonics Technology Letters **3**, (6), 570-572 (June 1991).

A.A. Godil, K.D. Li, and D.M. Bloom, "Pulsed FM Mode Locking of a Nd:BEL Laser," Optics Letters **16** (16), 1243-1245 (August 1991).

K.D. Li, J.A. Sheridan, and D.M. Bloom, "Picosecond pulse generation in Nd:BEL with a High-Frequency Acousto-Optic Mode Locker," Optics Letters **16**, (19), 1505-1507 (October, 1991)

Research Personnel

The following people participated in various portion of the research supported by this contract: Ekmel Özbay, Kathy Li Dessau, Julie Sheridan, John Thackara, Michael Kauffman, and David Bloom.

Oral Disclosures

E. Özbay, "2.0 psec GaAs Monolithic Photodiode and All-Electronic Sampler," The Topical Meeting on Picosecond Electronics and Optoelectronics, Optical Society of America, Salt Lake City (March 1991)

E. Özbay, "110 GHz Monolithic Resonant Tunneling Diode Trigger Circuit," The Topical Meeting on Picosecond Electronics and Optoelectronics, Optical Society of America, Salt Lake City (March 1991, Invited)

K.D. Li, E. Özbay, J.A. Sheridan, and D.M. Bloom, "1.8ps, 200 GHz GaAs Monolithic Photodiode and All-Electronic Sampler," presented at the Conference of Lasers and Electro-Optics 1991 postdeadline session, CPDP19, p. 608.

Patents

An invention disclosure has been filed for the idea using erbium doped fiber optical amplifiers in electro-optic testing systems.

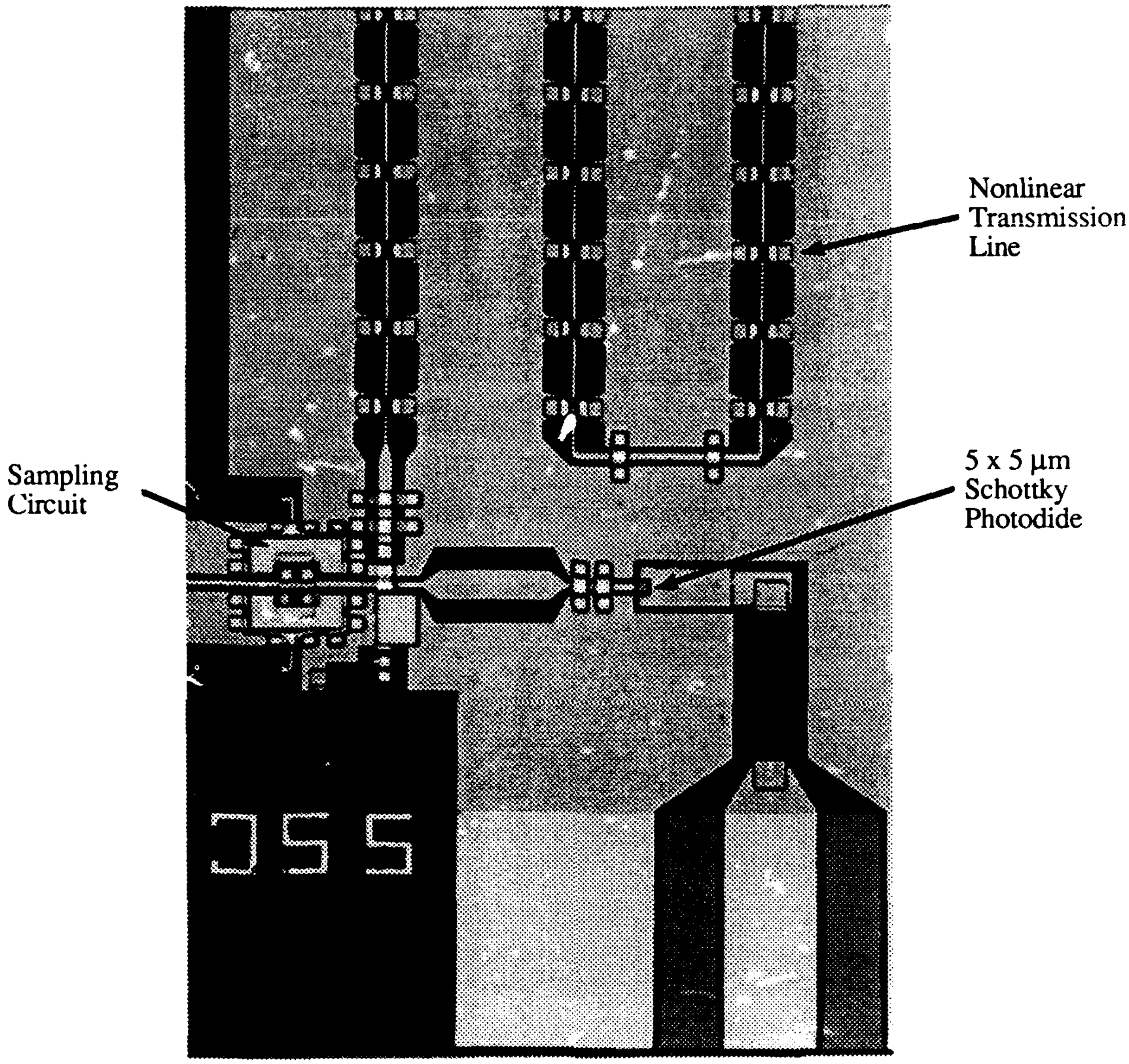


Figure 1: Photograph of photodide sampling circuit showing the nonlinear transmission line strobe pulse generator, the sampling circuit, and the Schottky photodiode.

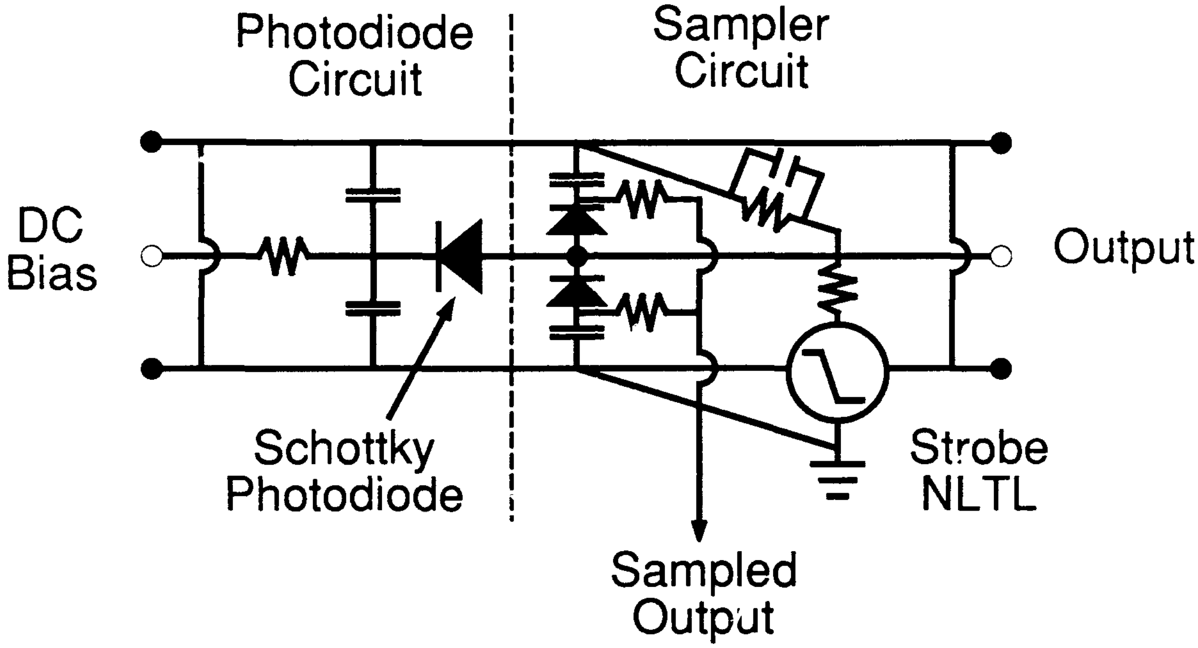
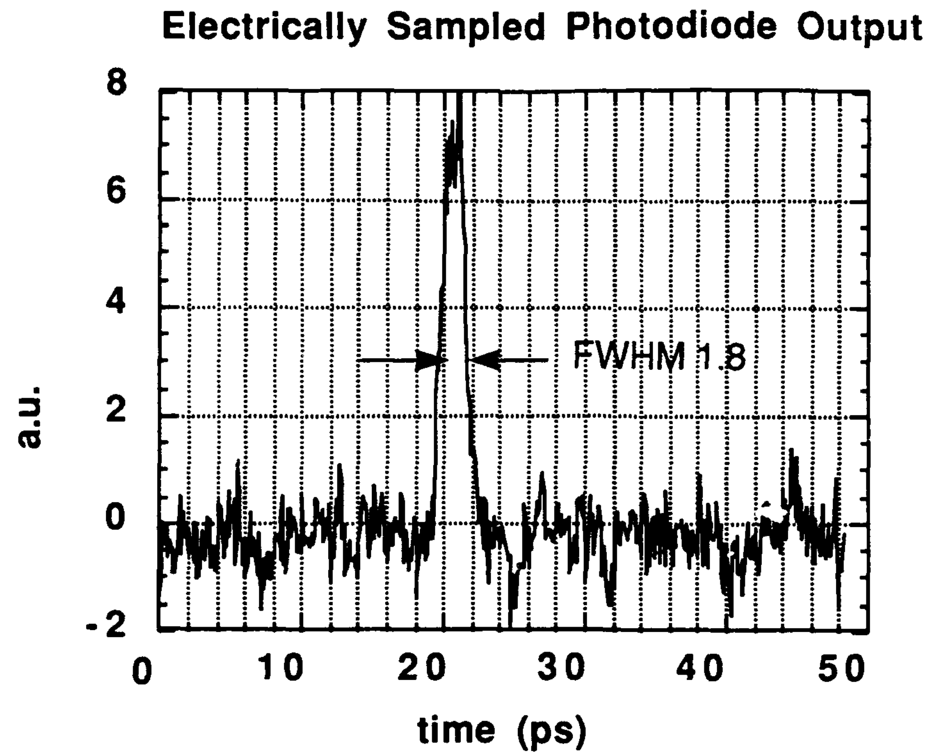
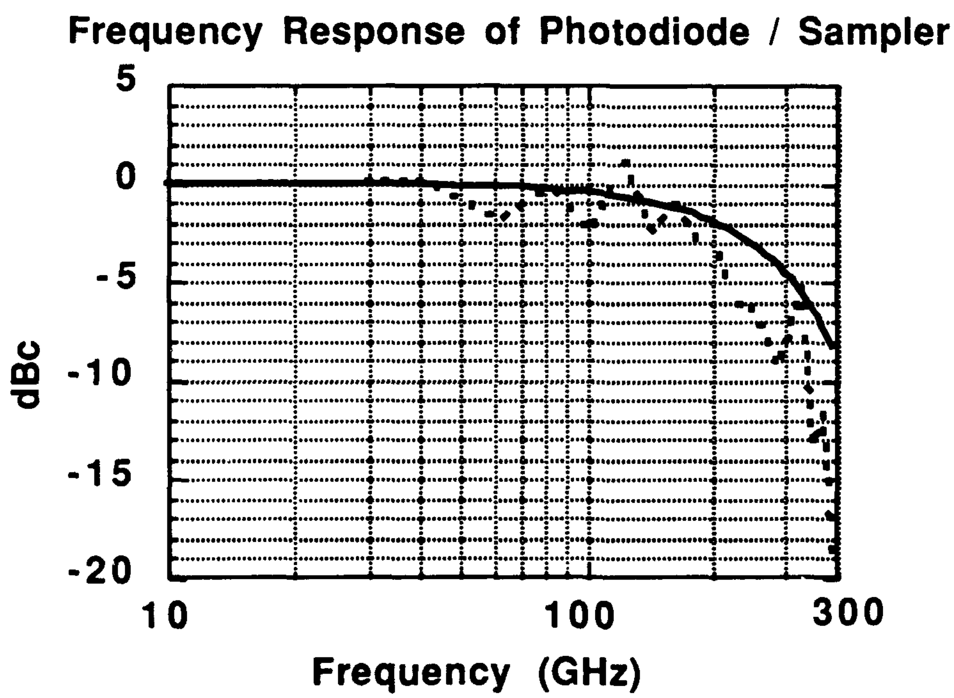


Figure 2: Circuit schematic of the p'.otodiode, sampler and nonlinear transmission line (NLTL) strobe



(a)



(b)

Figure 3: Electronically sampled output of the photodiode.
a) Measured time response of photodiode and sampler.
b) Fourier transform of the measured data (broken line), and of the measured data with backgound noise removed (solid line).

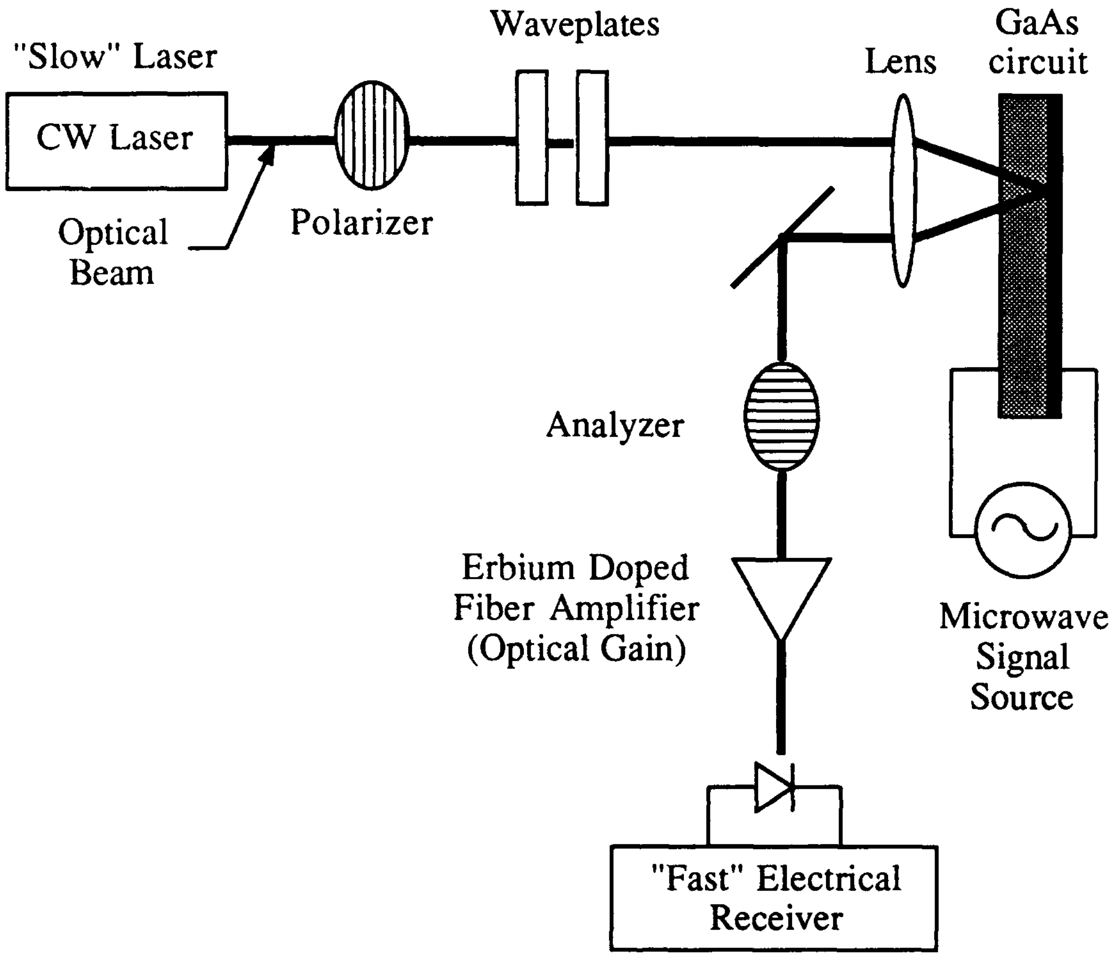


Figure 4: Proposed "fast electronics" electro-optic testing system including optical amplifier.

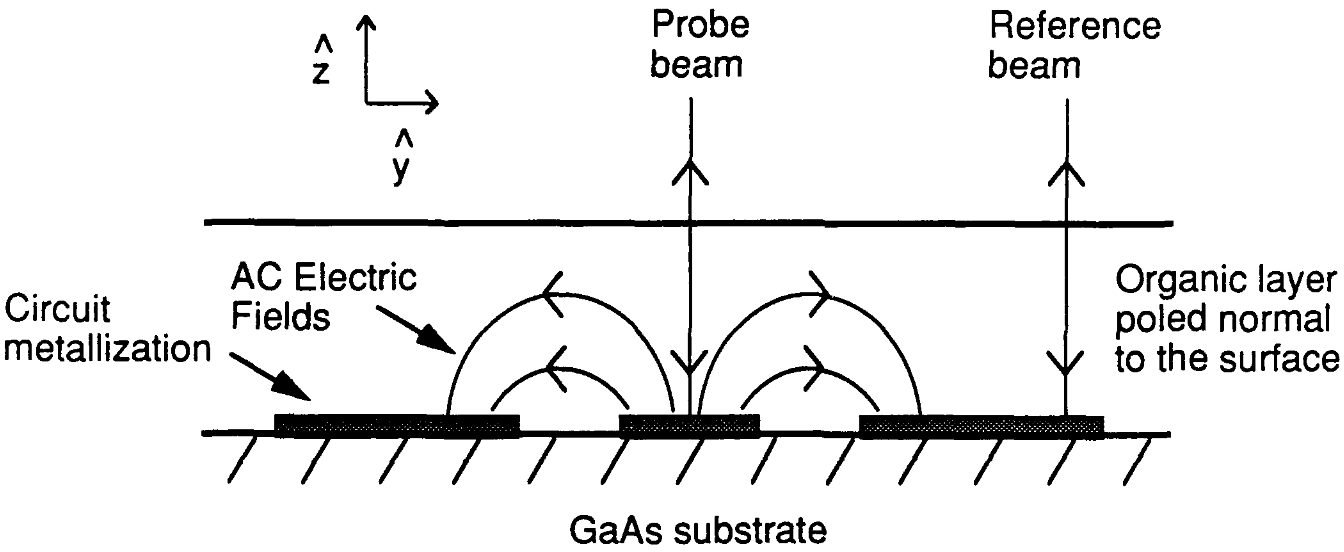


Figure 5: EO sampling geometry used for organic electro-optic films deposited directly onto the circuit under test.

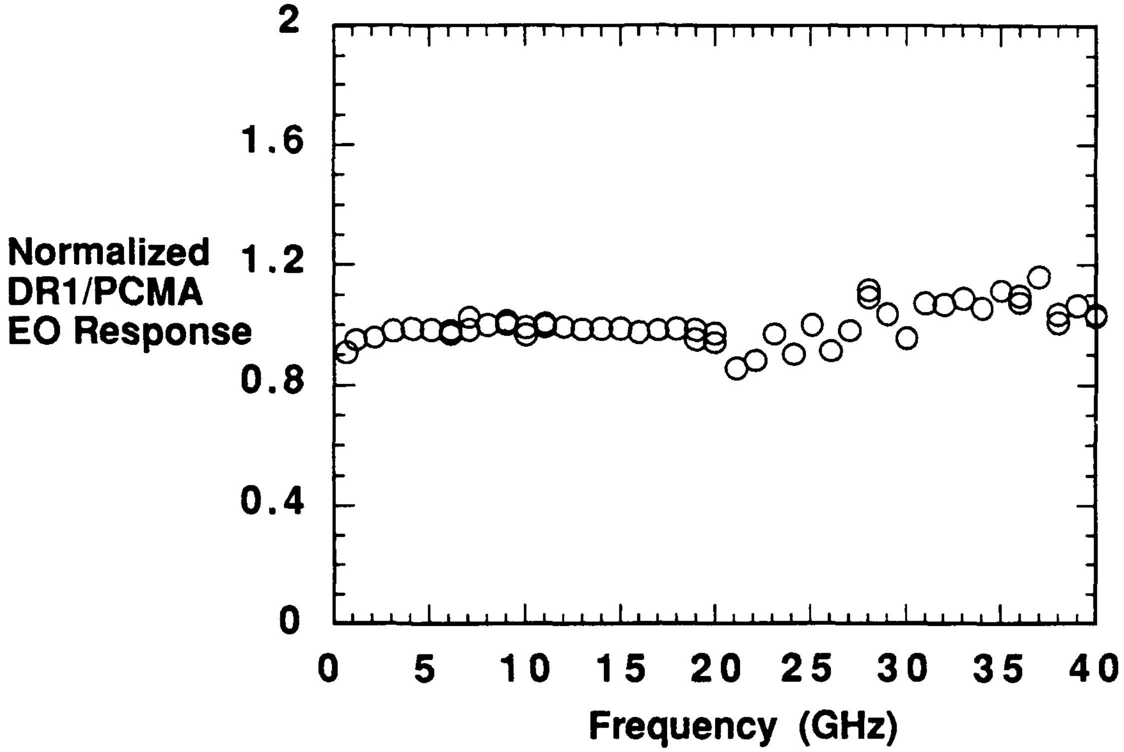


Figure 6: Normalized EO response for DR1/PCMA obtained from sampling both sides of the structure of Figure 5 in the Ginzton Ultrafast Electronics Laboratory EO sampling system. The fluctuations in the 20 to 40 GHz results are a consequence of the lower rf drive power available over this frequency range.

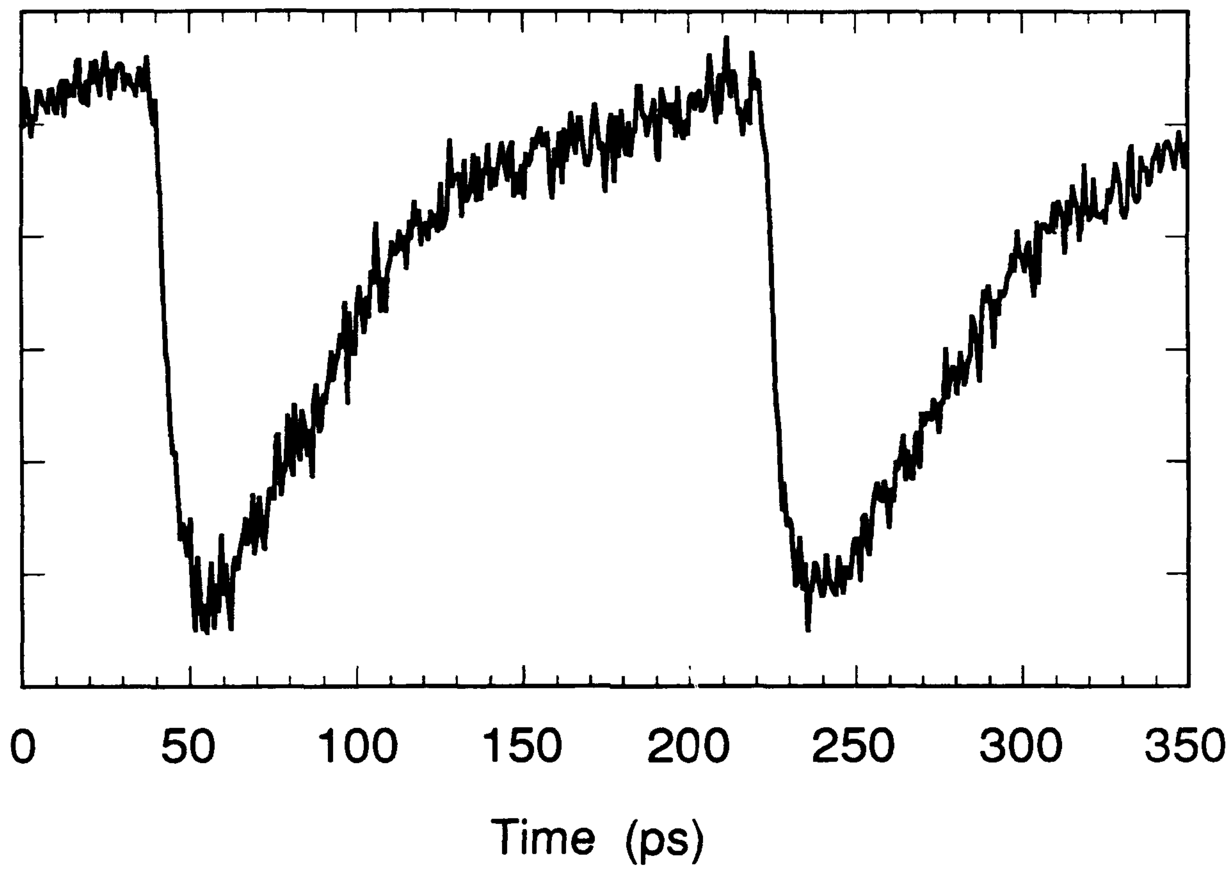


Figure 7: Nonlinear transmission line output sampled via a 19 μm thick DR1/PCMA layer which was poled on top of the circuit. The waveform shown is an average of 100 traces.